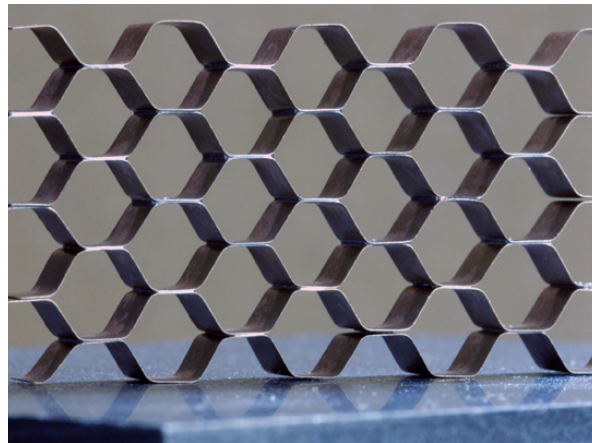


# Cellular Shape Memory Alloy Structures: Experiments & Modeling



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# Outline

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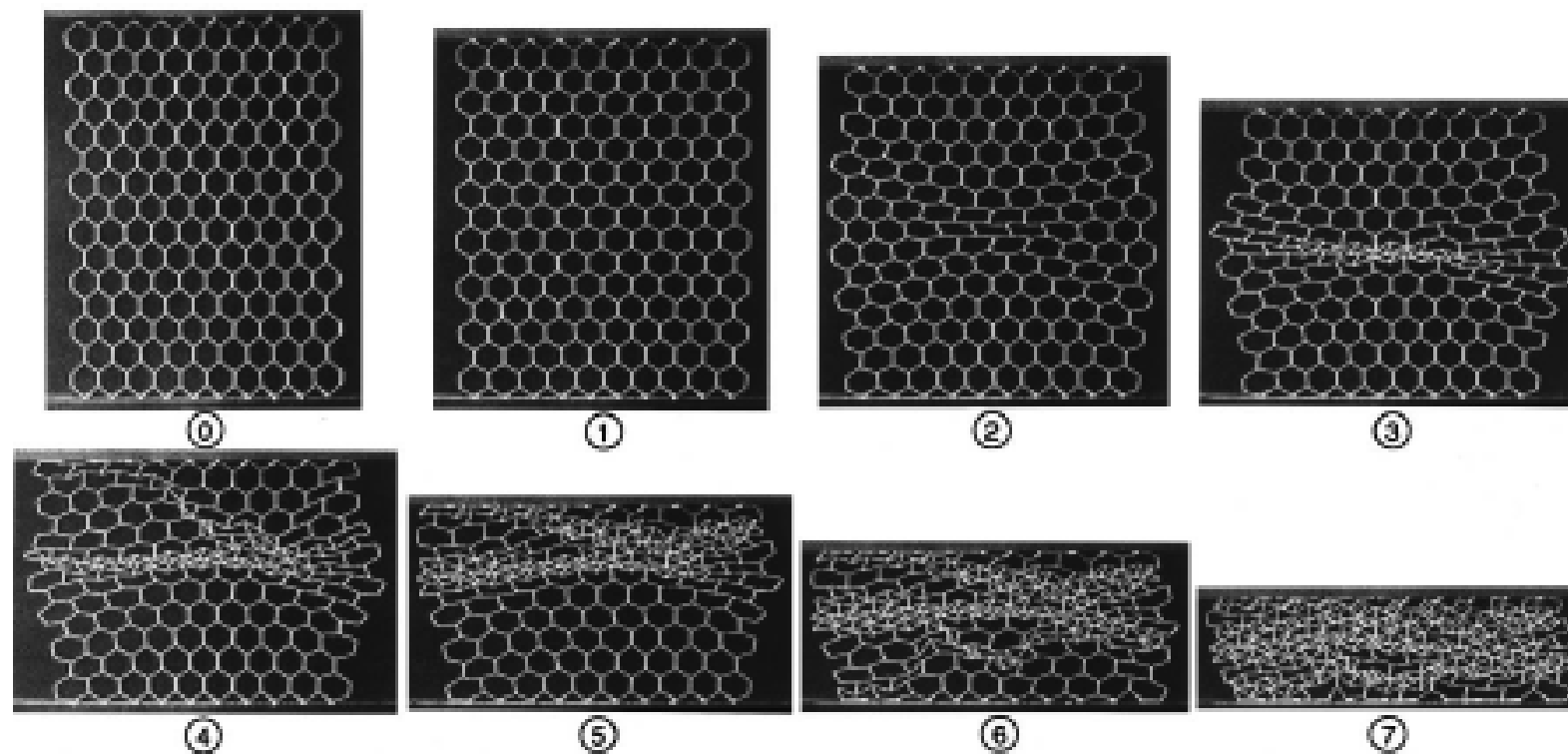
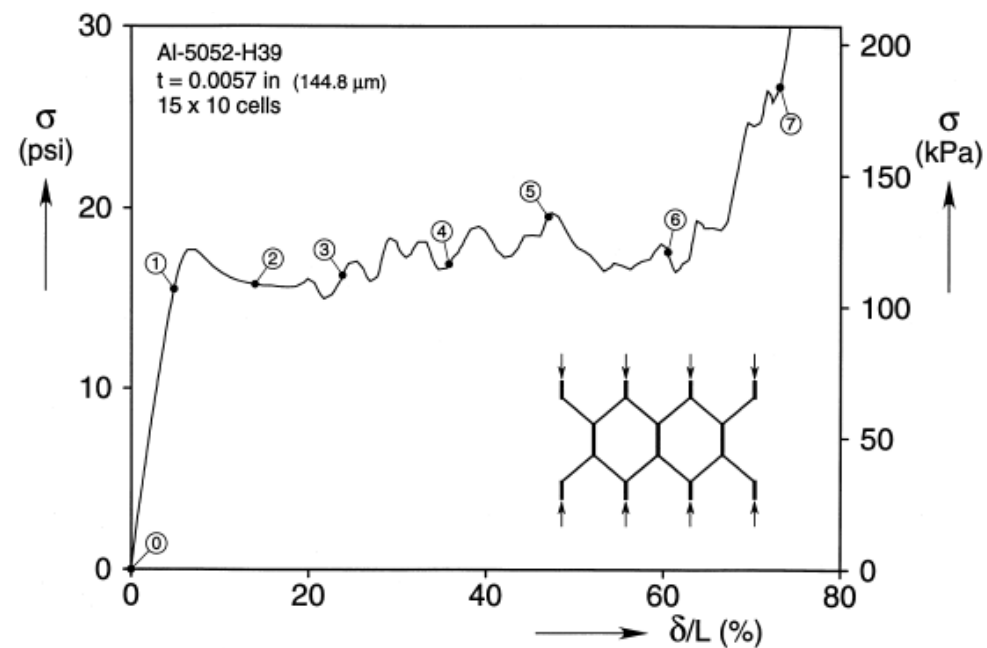
- Background
- Honeycomb specimen fabrication
- Honeycomb characterization
- SMA bending



# Background

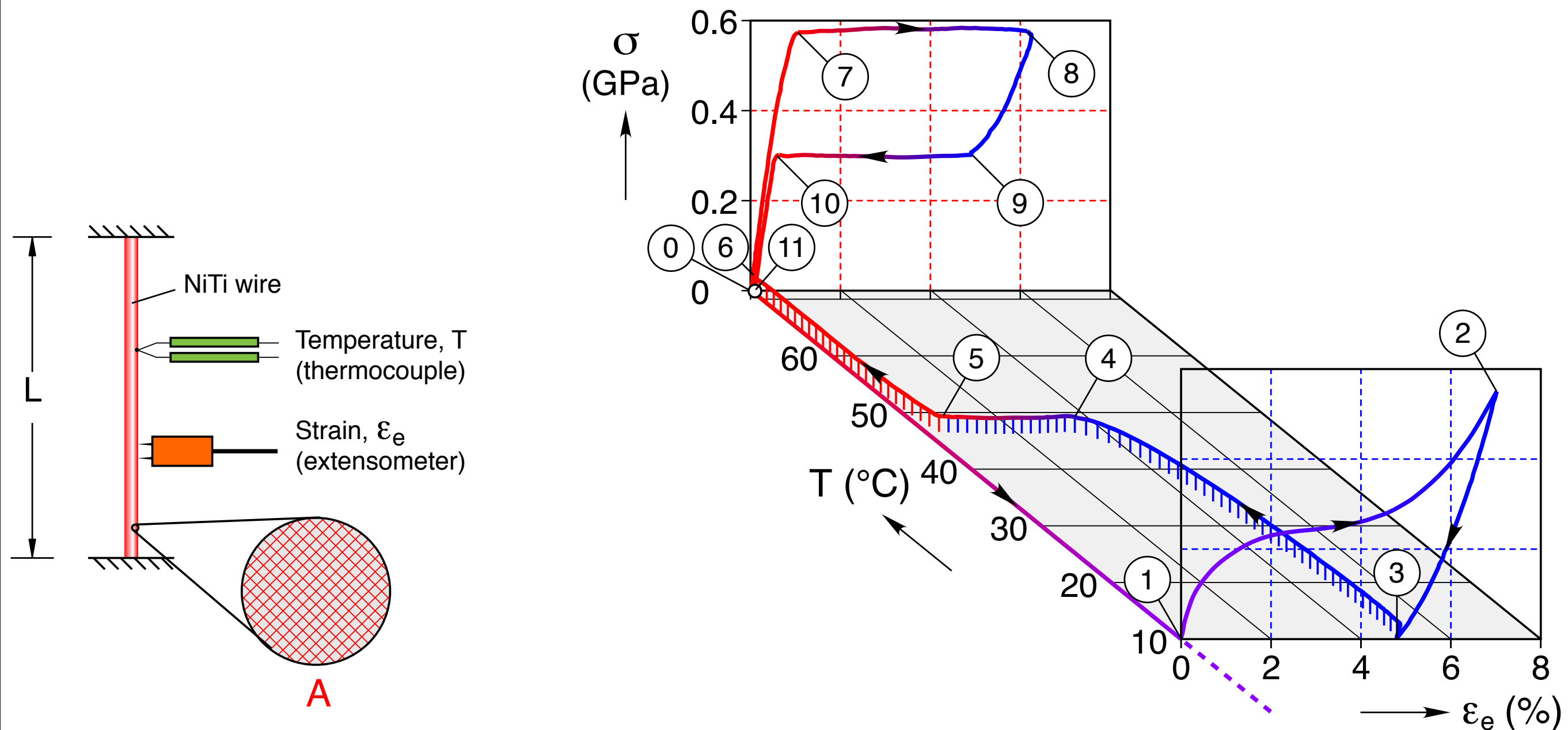


# Compression of Al honeycomb



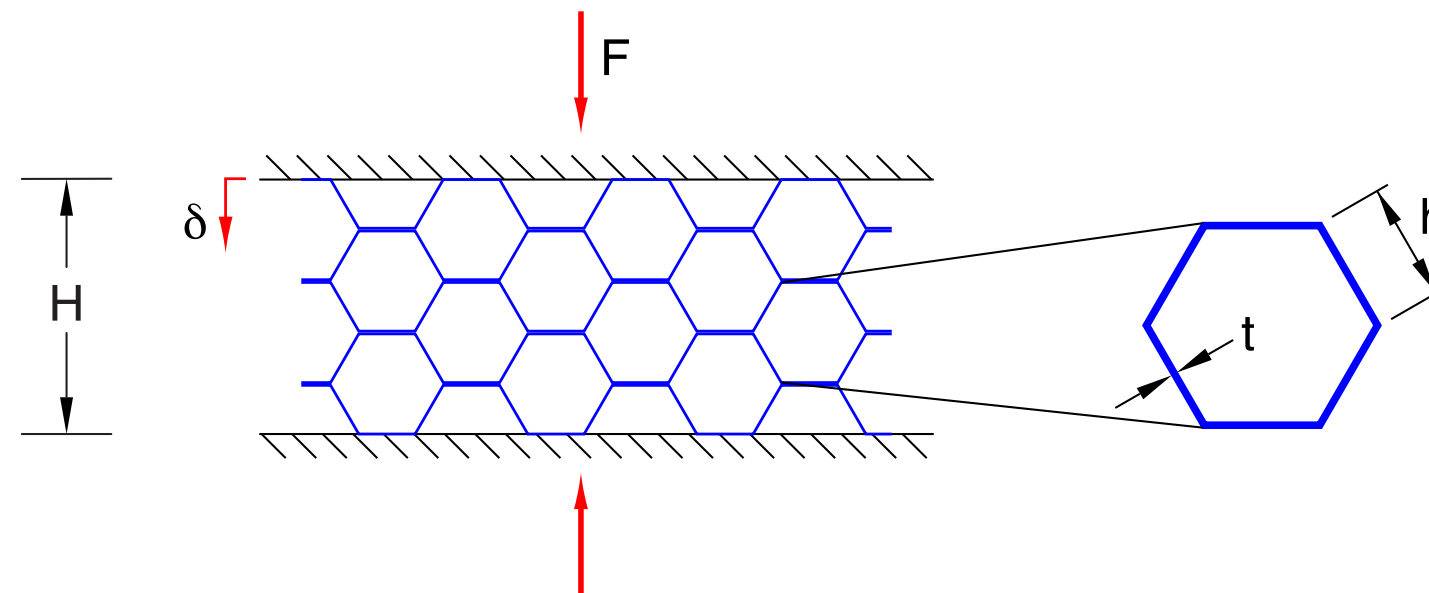
[Papka/Kyriakides, 1998]

# Nitinol (SM) wire: shape memory & superelasticity



## Shape memory & superelasticity

# Thin-walled honeycomb: scaling laws



Comparison of Aluminum & NiTi honeycomb  
for same recoverable global strain

Property	Al	NiTi	NiTi/Al
$\varepsilon_{\text{dense}}^*$	-50%	-50%	1
$\varepsilon_{\text{s,max}}$	0.5%	5%	10
$t/h$	$10^{-2}$	$10^{-1}$	10
$ \sigma_0^* /\sigma_{\text{s},0}$	$10^{-4}$	$10^{-2}$	100
$E^*/E_{\text{s}}$	$10^{-6}$	$10^{-3}$	1000

relative density

$$\frac{\rho^*}{\rho_{\text{s}}} \propto \frac{t}{h}$$

global/local bending strain

$$\frac{|\varepsilon_{\text{dense}}^*|}{\varepsilon_{\text{s,max}}} \propto \frac{t}{h}$$

global/local plateau stress

$$\frac{|\sigma_0^*|}{\sigma_{\text{s},0}} \propto \left(\frac{t}{h}\right)^2$$

global/local modulus

$$\frac{E^*}{E_{\text{s}}} \propto \left(\frac{t}{h}\right)^3$$

[Gibson/Ashby, 1997]

# Advantages of SMA honeycombs

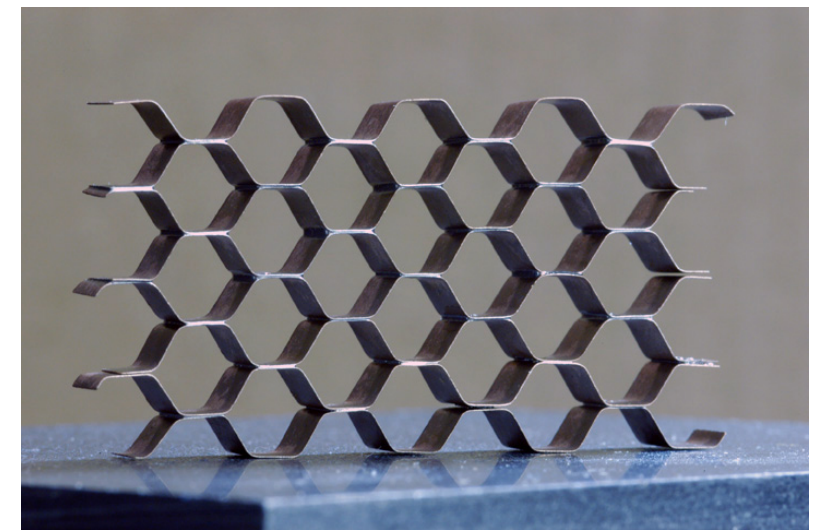
Combine benefits of light-weight cellular structures with Shape Memory Alloy (SMA) adaptive behavior

## Metallic honeycombs

- Low density
- High specific stiffness
- Large specific energy absorption

### Combination

- Amplified strain recovery  
5% ➔ 50%
- Reduced thermal lag  
 $\tau \rightarrow \tau / 10$



NiTi hexagonal honeycomb  
(5.7% dense, 0.37 g/cc)

## NiTi SMA

- Shape memory effect & superelasticity
- High strength, ductility,
- Corrosion resistance, biocompatibility



## Overload protection

- Amplified superelasticity, reusable energy absorber
- Lightweight, resilient, damage tolerant

## Vibration isolation

- Adaptive damping

## Thermal actuators & adaptive structures

- Improved response time, amplified stroke

## Thermal & acoustic management

- Adaptive thermal conductivity & acoustic impedance

## Biomedical implants & devices

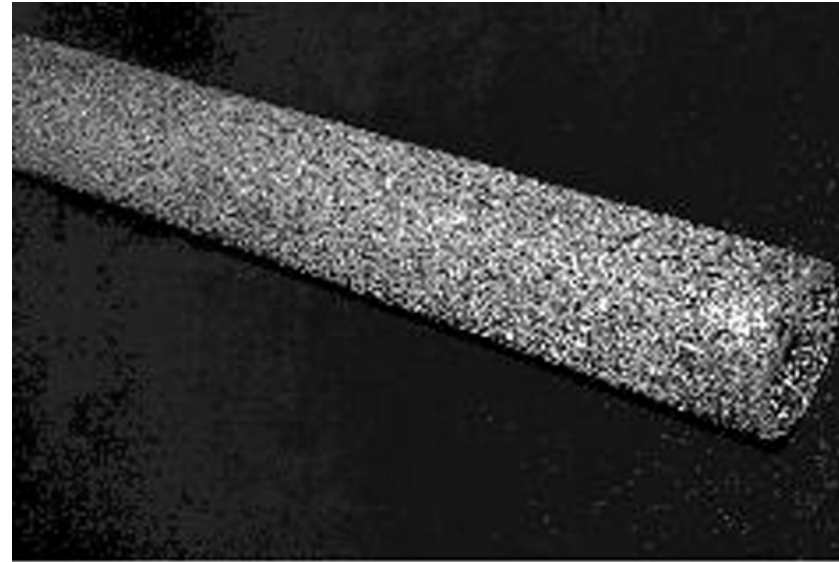
- Lightweight, sparse, tailorable properties, deployable

# Fabrication & Metallurgy

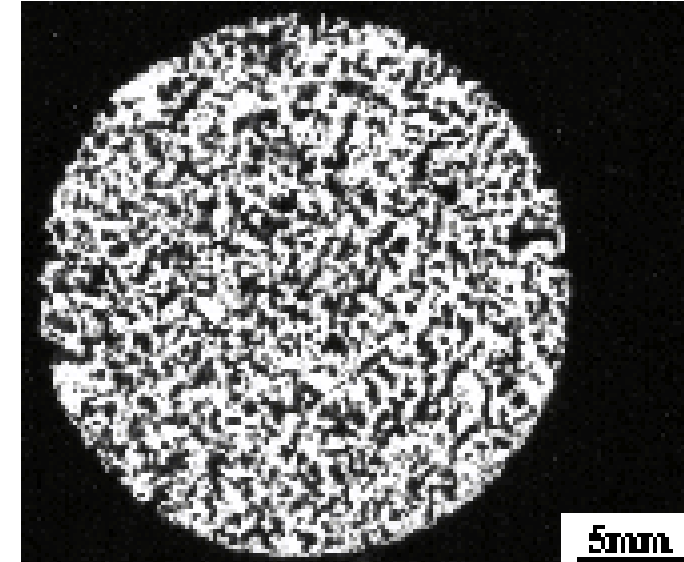


## Prior Attempts: Powder Metallurgy

### Porous SMAs

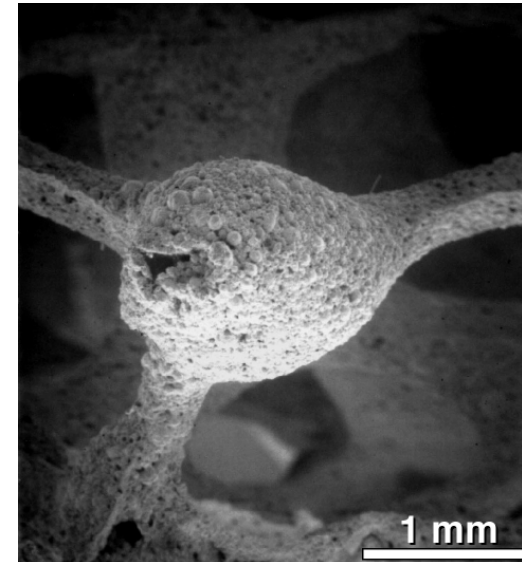


50% dense NiTi bar  
hot isostatic pressing of elemental powders  
[Naval Research Lab, V. DeGiorgi]



40% dense NiTi bar  
combustion synthesis  
[Li Rong, China]

### SMA foam



5% dense NiTi open-cell foam  
Powder process with sacrificial precursor  
[Grummon/Shaw, 2002]

# Technological Barrier Overcome

## Long-standing difficulty:

- Joining NiTi to itself or anything else
- Usually requires mechanical attachment/crimping
- Gluing is a very low strength option

## Metallurgical bonds:

- Sensitive to interstitial contaminants (C, O, N).
- Laser welding in inert gas
  - Tricky (& proprietary), but some recent success.
  - Requires line-of-sight access.
- Soldering
  - Requires very aggressive fluxes to remove Ti-oxides.
  - Low strength
- Nb-reactive bonding (our process)
  - Discovered in 2004
  - Self-fluxing
  - Strong, ductile joints
  - Vanadium also works well





**The periodic table of the elements**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Alkali metals (not H)	Alkaline earth metals	Rare earths (Sc, Y, and La-Lu)								Coinage metals (not Rg)				pnictogens	chalcogens	halogens	noble gases
1 <b>H</b> 1.0079 Hydrogen																	2 <b>He</b> 4.0026 Helium
3 <b>Li</b> 6.941 Lithium	4 <b>Be</b> 9.0122 Beryllium											5 <b>B</b> 10.811 Boron	6 <b>C</b> 12.011 Carbon	7 <b>N</b> 14.007 Nitrogen	8 <b>O</b> 15.999 Oxygen	9 <b>F</b> 18.998 Fluorine	10 <b>Ne</b> 20.180 Neon
11 <b>Na</b> 22.990 Sodium	12 <b>Mg</b> 24.305 Magnesium											13 <b>Al</b> 26.982 Aluminum	14 <b>Si</b> 28.086 Silicon	15 <b>P</b> 30.974 Phosphorus	16 <b>S</b> 32.065 Sulfur	17 <b>Cl</b> 35.453 Chlorine	18 <b>Ar</b> 39.948 Argon
19 <b>K</b> 39.098 Potassium	20 <b>Ca</b> 40.078 Calcium	21 <b>Sc</b> 44.956 Scandium	22 <b>Ti</b> 47.867 Titanium	23 <b>V</b> 50.942 Vanadium	24 <b>Cr</b> 51.996 Chromium	25 <b>Mn</b> 54.938 Manganese	26 <b>Fe</b> 55.845 Iron	27 <b>Co</b> 58.933 Cobalt	28 <b>Ni</b> 58.693 Nickel	29 <b>Cu</b> 63.546 Copper	30 <b>Zn</b> 65.38 Zinc	31 <b>Ga</b> 69.723 Gallium	32 <b>Ge</b> 72.64 Germanium	33 <b>As</b> 74.922 Arsenic	34 <b>Se</b> 78.96 Selenium	35 <b>Br</b> 79.904 Bromine	36 <b>Kr</b> 83.798 Krypton
37 <b>Rb</b> 85.468 Rubidium	38 <b>Sr</b> 87.62 Strontium	39 <b>Y</b> 88.906 Yttrium	40 <b>Zr</b> 91.224 Zirconium	41 <b>Nb</b> 92.906 Niobium	42 <b>Mo</b> 95.96 Molybdenum	43 <b>Tc</b> [97.907] Technetium	44 <b>Ru</b> 101.07 Ruthenium	45 <b>Rh</b> 102.91 Rhodium	46 <b>Pd</b> 106.42 Palladium	47 <b>Ag</b> 107.87 Silver	48 <b>Cd</b> 112.41 Cadmium	49 <b>In</b> 114.82 Indium	50 <b>Sn</b> 118.71 Tin	51 <b>Sb</b> 121.76 Antimony	52 <b>Te</b> 127.60 Tellurium	53 <b>I</b> 126.90 Iodine	54 <b>Xe</b> 131.29 Xenon
55 <b>Cs</b> 132.91 Cesium	56 <b>Ba</b> 137.33 Barium	71 <b>Lu</b> 174.97 Lutetium	72 <b>Hf</b> 178.49 Hafnium	73 <b>Ta</b> 180.95 Tantalum	74 <b>W</b> 183.84 Tungsten	75 <b>Re</b> 186.21 Rhenium	76 <b>Os</b> 190.23 Osmium	77 <b>Ir</b> 192.22 Iridium	78 <b>Pt</b> 195.08 Platinum	79 <b>Au</b> 196.97 Gold	80 <b>Hg</b> 200.59 Mercury	81 <b>Tl</b> 204.38 Thallium	82 <b>Pb</b> 207.2 Lead	83 <b>Bi</b> 208.98 Bismuth	84 <b>Po</b> [208.98] Polonium	85 <b>At</b> [209.99] Astatine	86 <b>Rn</b> [222.02] Radon
87 <b>Fr</b> [223.02] Francium	88 <b>Ra</b> [226.03] Radium	103 <b>Lr</b> [262.11] Lawrencium	104 <b>Rf</b> [267.12] Rutherfordium	105 <b>Db</b> [268.13] Dubnium	106 <b>Sg</b> [271.13] Seaborgium	107 <b>Bh</b> [272.14] Bohrium	108 <b>Hs</b> [269.13] Hassium	109 <b>Mt</b> [276.15] Meitnerium	110 <b>Ds</b> [281.16] Darmstadtium	111 <b>Rg</b> [280.16] Roentgenium	112 <b>Cn</b> [285.17] Copernicium	113 <b>Uut</b> [284.18] Ununtrium	114 <b>Uuq</b> [289.19] Ununquadium	115 <b>Uup</b> [288.19] Ununpentium	116 <b>Uuh</b> [293] Ununhexium	117 <b>Uus</b> [294] Ununseptium	118 <b>Uuo</b> [294] Ununoctium
Lanthanoids (lanthanides) 15 elements La-Lu		57 <b>La</b> 138.91 Lanthanum	58 <b>Ce</b> 140.12 Cerium	59 <b>Pr</b> 140.91 Praseodymium	60 <b>Nd</b> 144.24 Neodymium	61 <b>Pm</b> [144.91] Promethium	62 <b>Sm</b> 150.36 Samarium	63 <b>Eu</b> 151.96 Europium	64 <b>Gd</b> 157.25 Gadolinium	65 <b>Tb</b> 158.93 Terbium	66 <b>Dy</b> 162.50 Dysprosium	67 <b>Ho</b> 164.93 Holmium	68 <b>Er</b> 167.26 Erbium	69 <b>Tm</b> 168.93 Thulium	70 <b>Yb</b> 173.05 Ytterbium		
Actinoids (actinides) 15 elements Ac-Lr		89 <b>Ac</b> [227.03] Actinium	90 <b>Th</b> 232.04 Thorium	91 <b>Pa</b> 231.04 Protactinium	92 <b>U</b> 238.03 Uranium	93 <b>Np</b> [237.05] Neptunium	94 <b>Pu</b> [244.06] Plutonium	95 <b>Am</b> [243.06] Americium	96 <b>Cm</b> [247.07] Curium	97 <b>Bk</b> [247.07] Berkelium	98 <b>Cf</b> [251.08] Californium	99 <b>Es</b> [252.08] Einsteinium	100 <b>Fm</b> [257.10] Fermium	101 <b>Md</b> [258.10] Mendelevium	102 <b>No</b> [259.10] Nobelium		

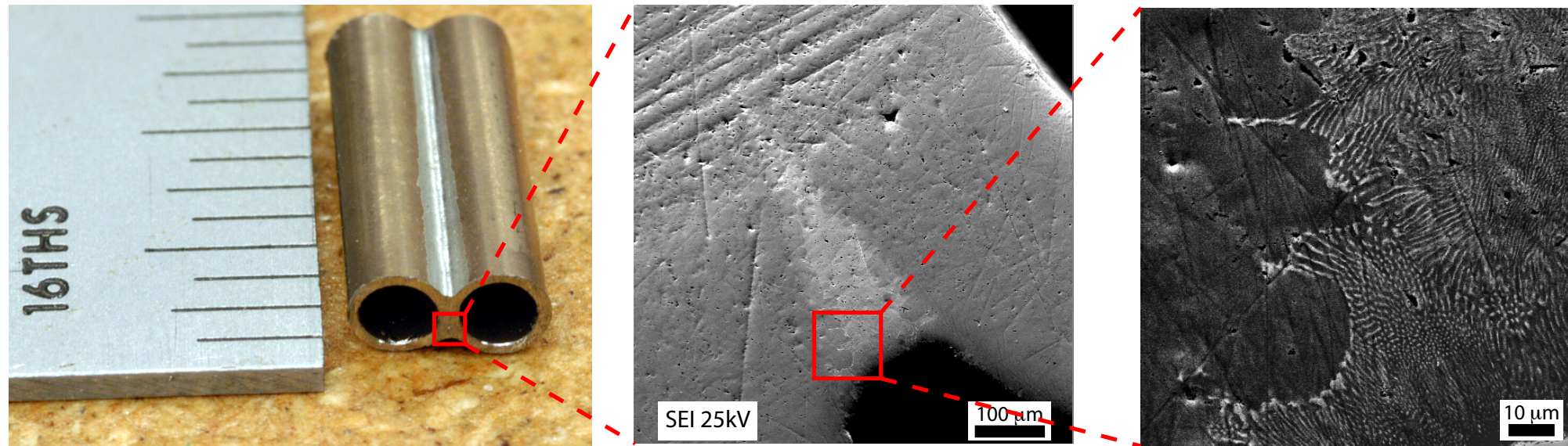
Symbol (solid liquid gas)  
 Atomic number  
 Relative atomic mass (atomic weight, 5 significant figures)  
 Element name Metal Semi-metal Non-metal

www.webelements.com





# Discovery of a Nb-based braze for joining wrought NiTi

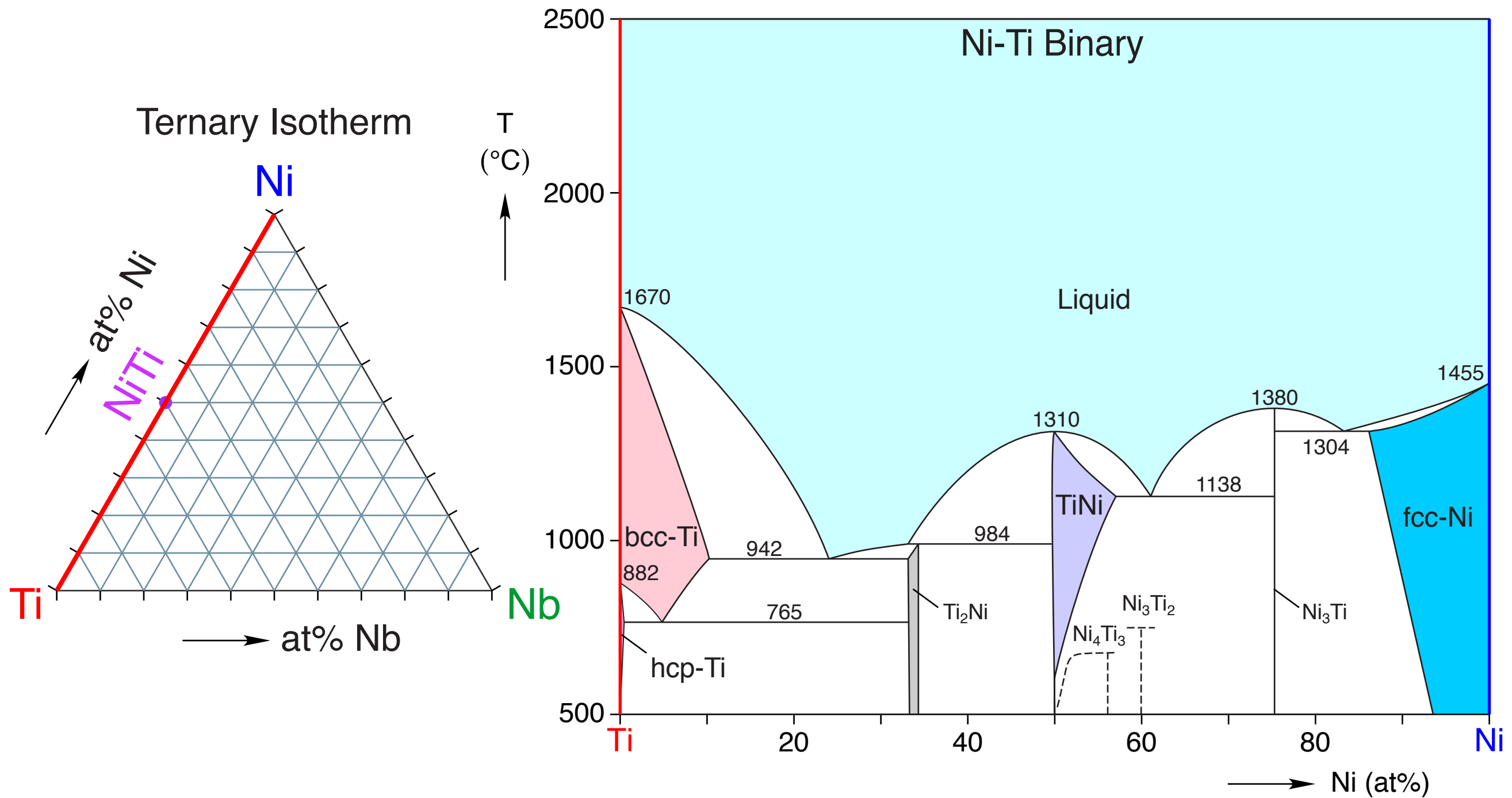


[Shaw/Grummon (UM/MSU) U.S. patent 7,896,222, issued March 1, 2011]

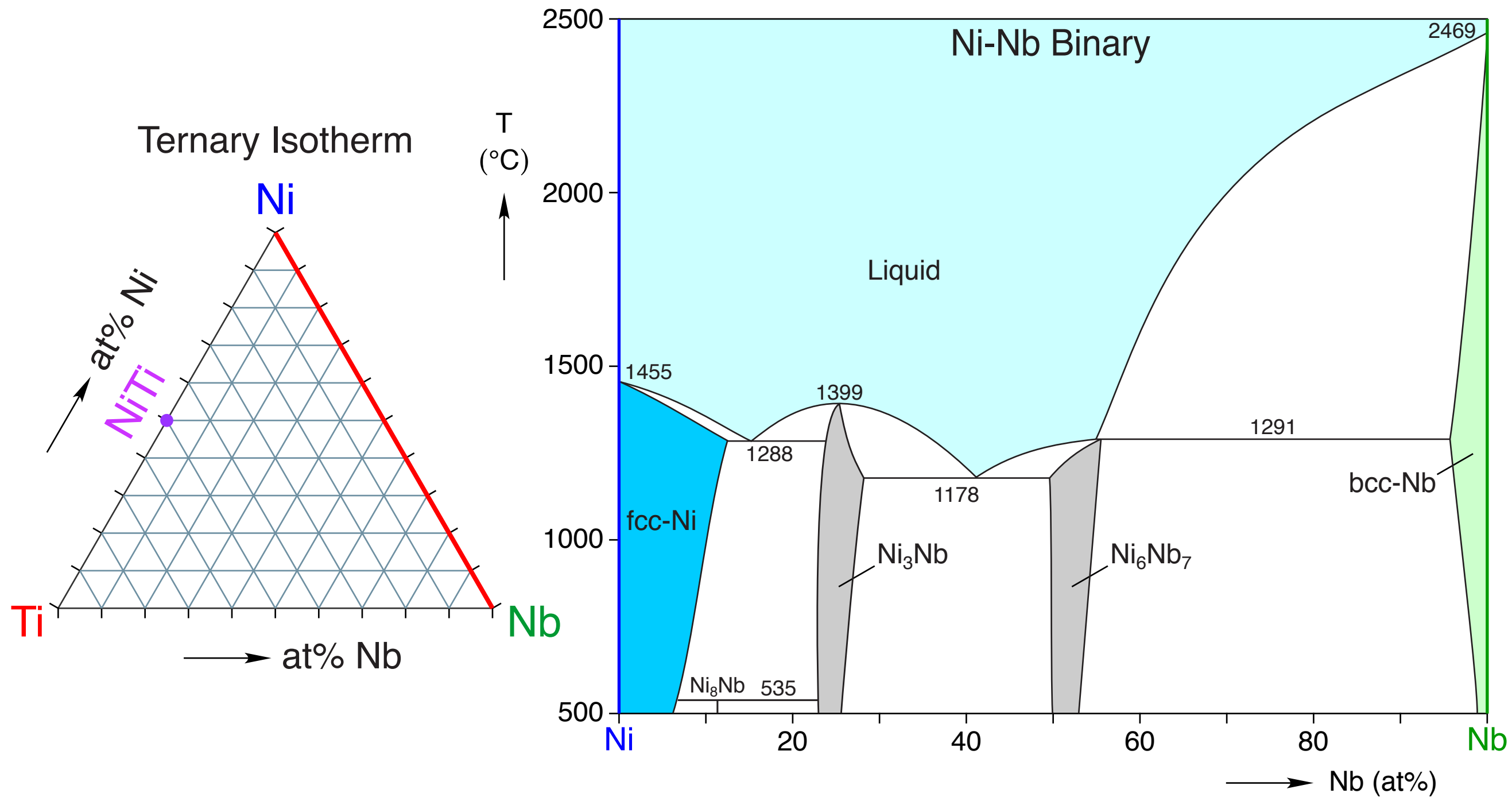


60 NiTi-tube array (32 % dense)

# Some Metallurgy

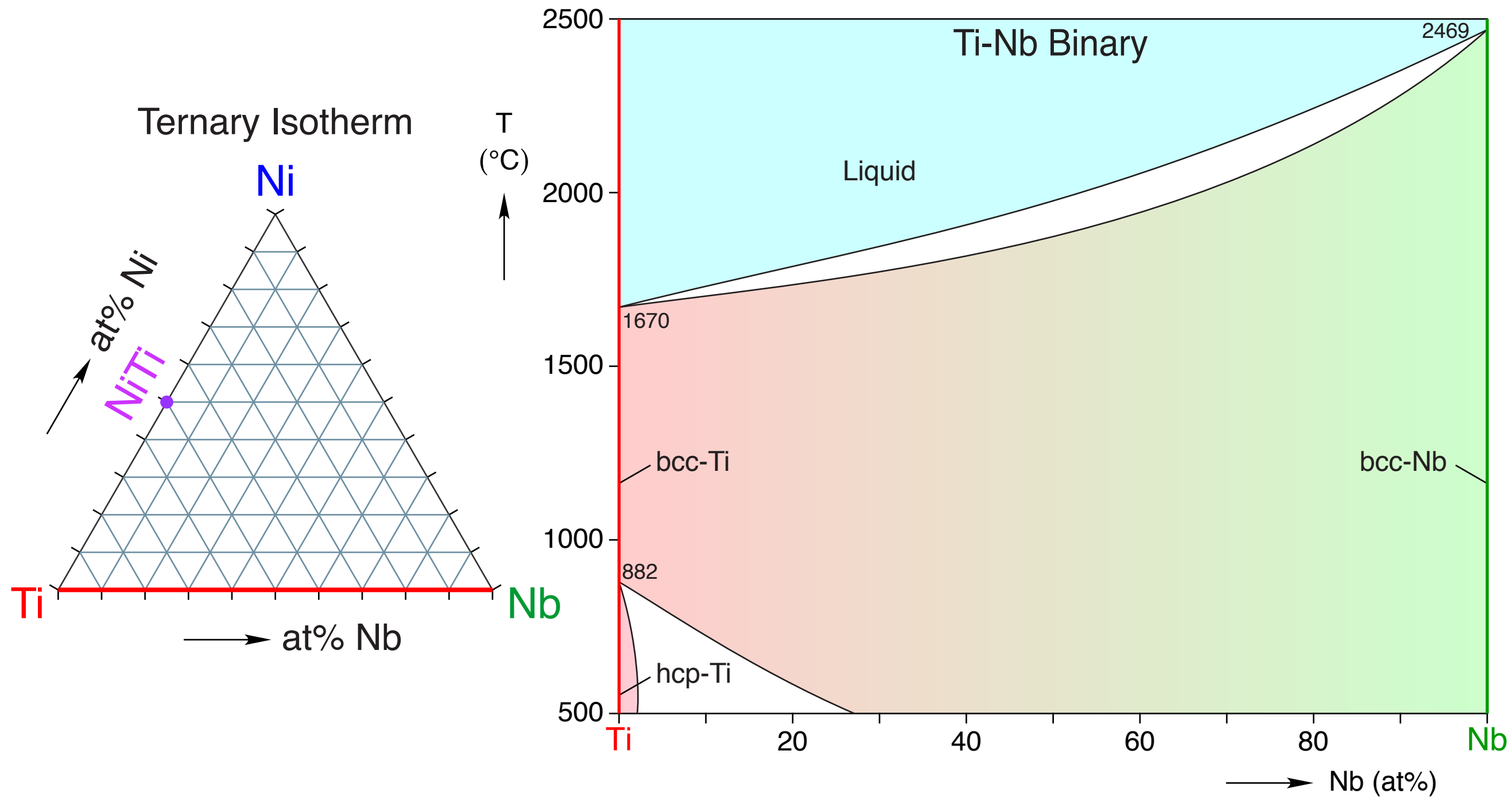


# Some Metallurgy

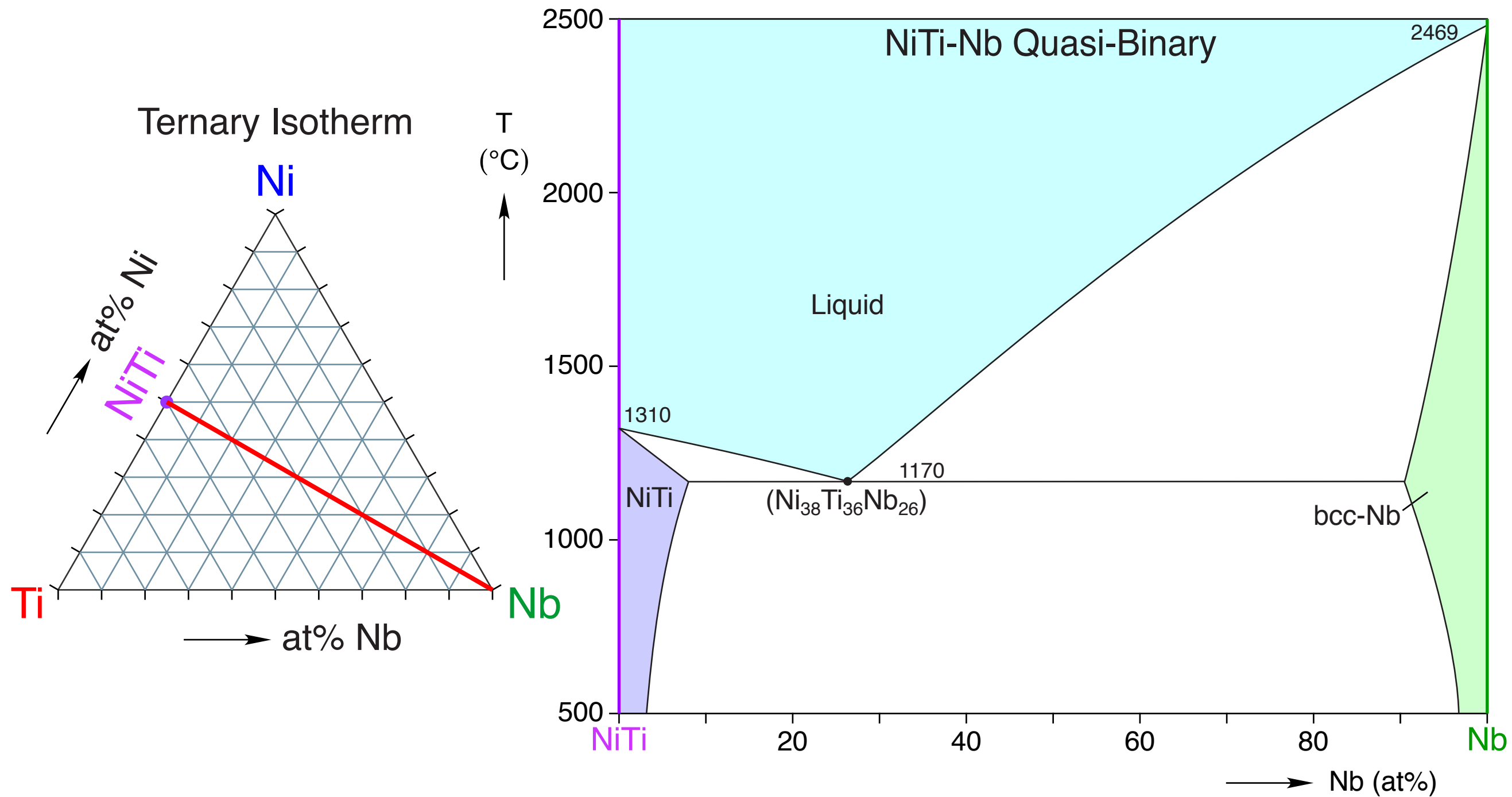




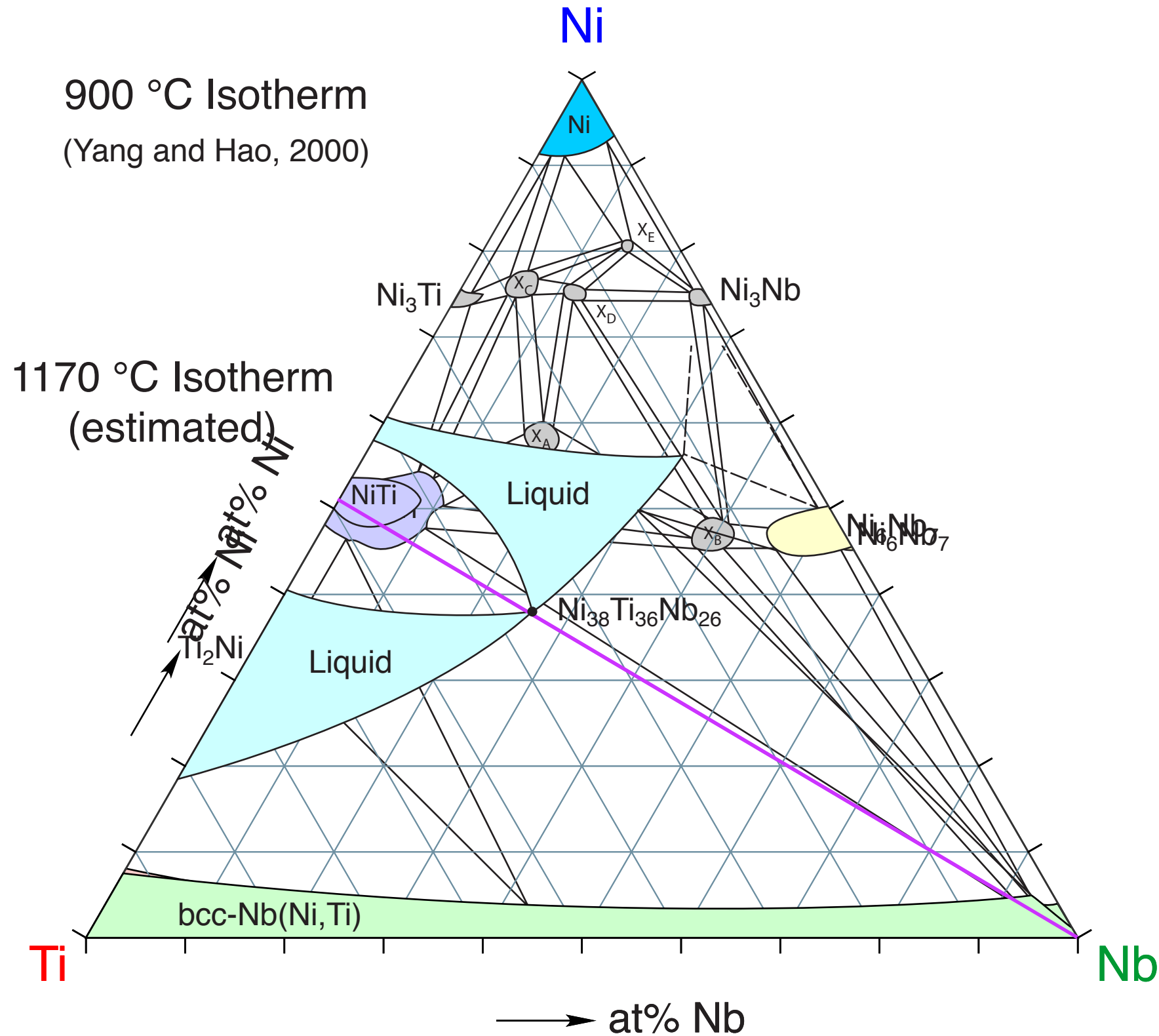
# Some Metallurgy



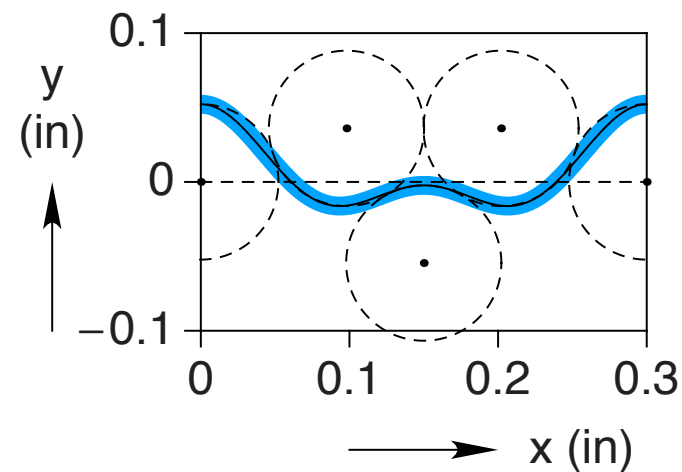
# Some Metallurgy



# Quasi-binary Eutectic



# Fabrication Procedure



Shape-set of corrugated strips (500 °C)

1. Corrugate SMA strips at 500 °C by shape set die
2. Lay up corrugation layers & Nb foils
3. Vacuum furnace at 1170 °C, 5 min
4. Age at 500 °C, 10 min

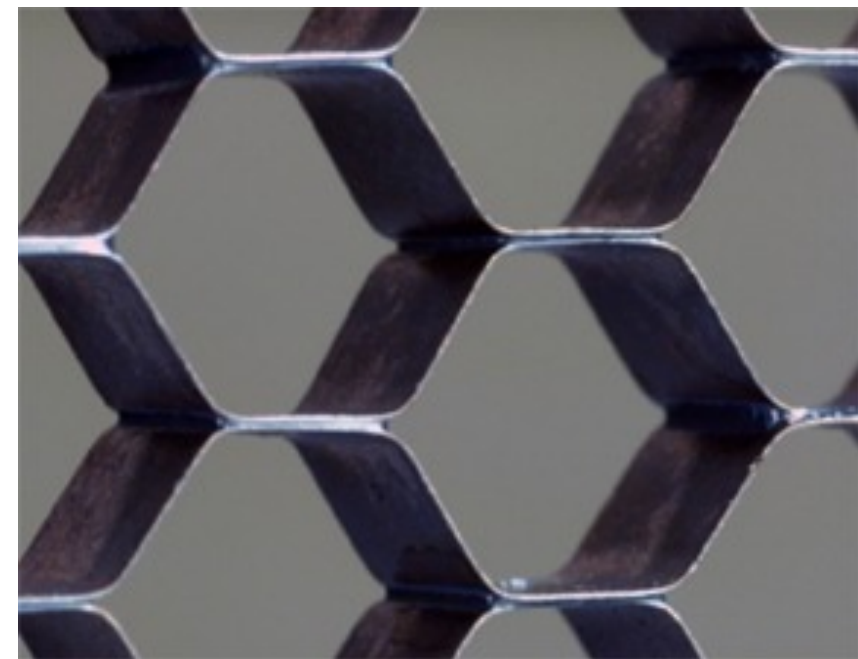
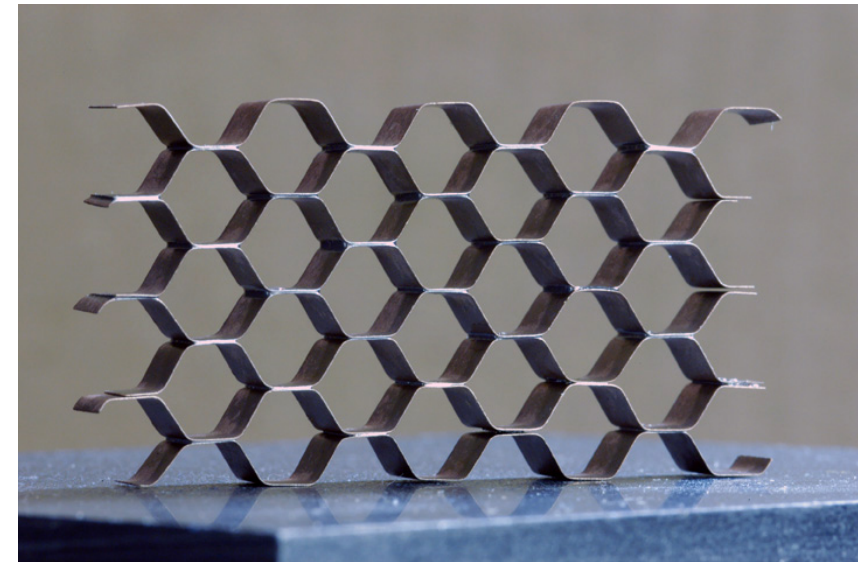




# Low-density NiTi cellular specimens



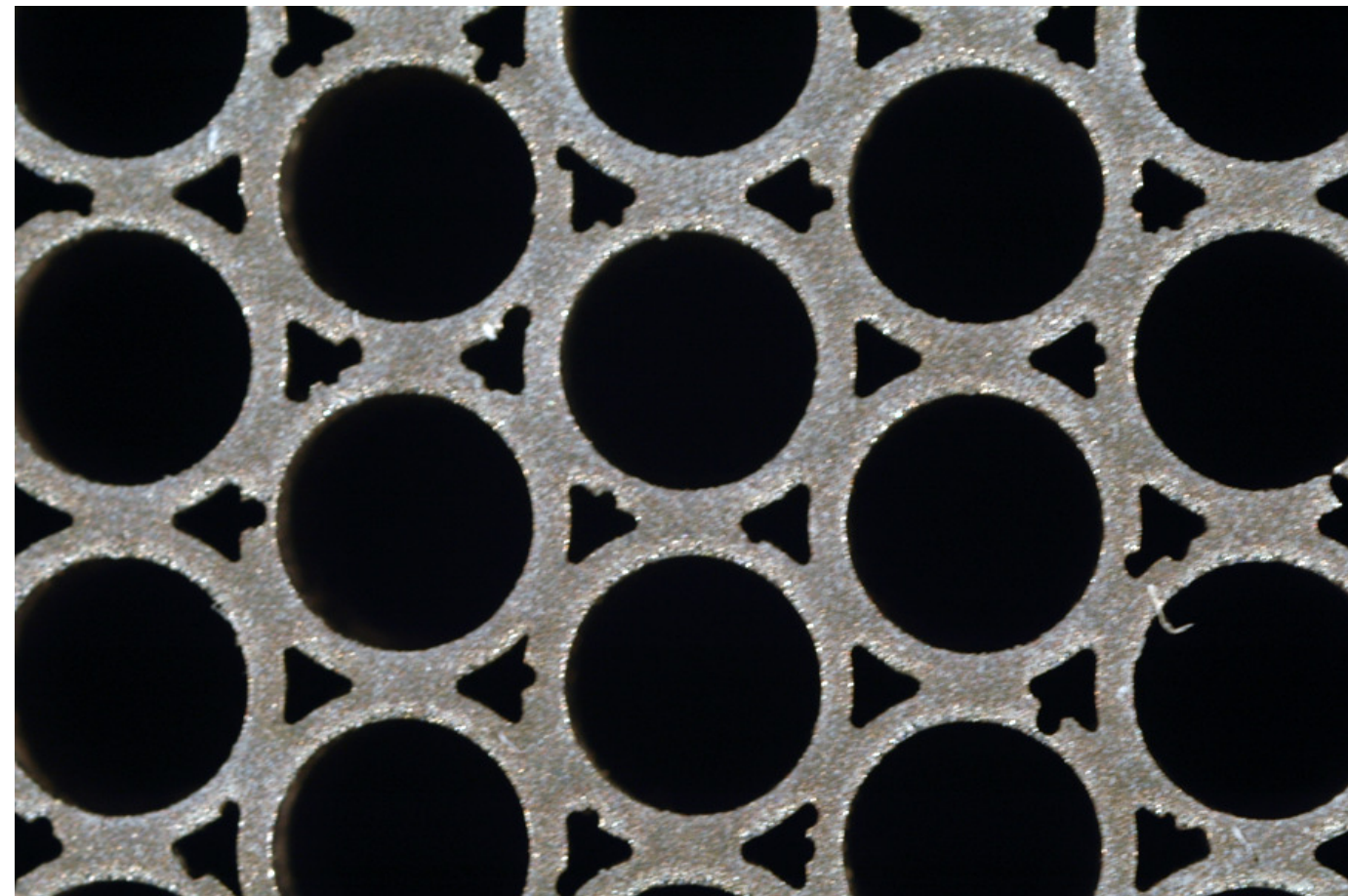
NiTi wavy corrugations

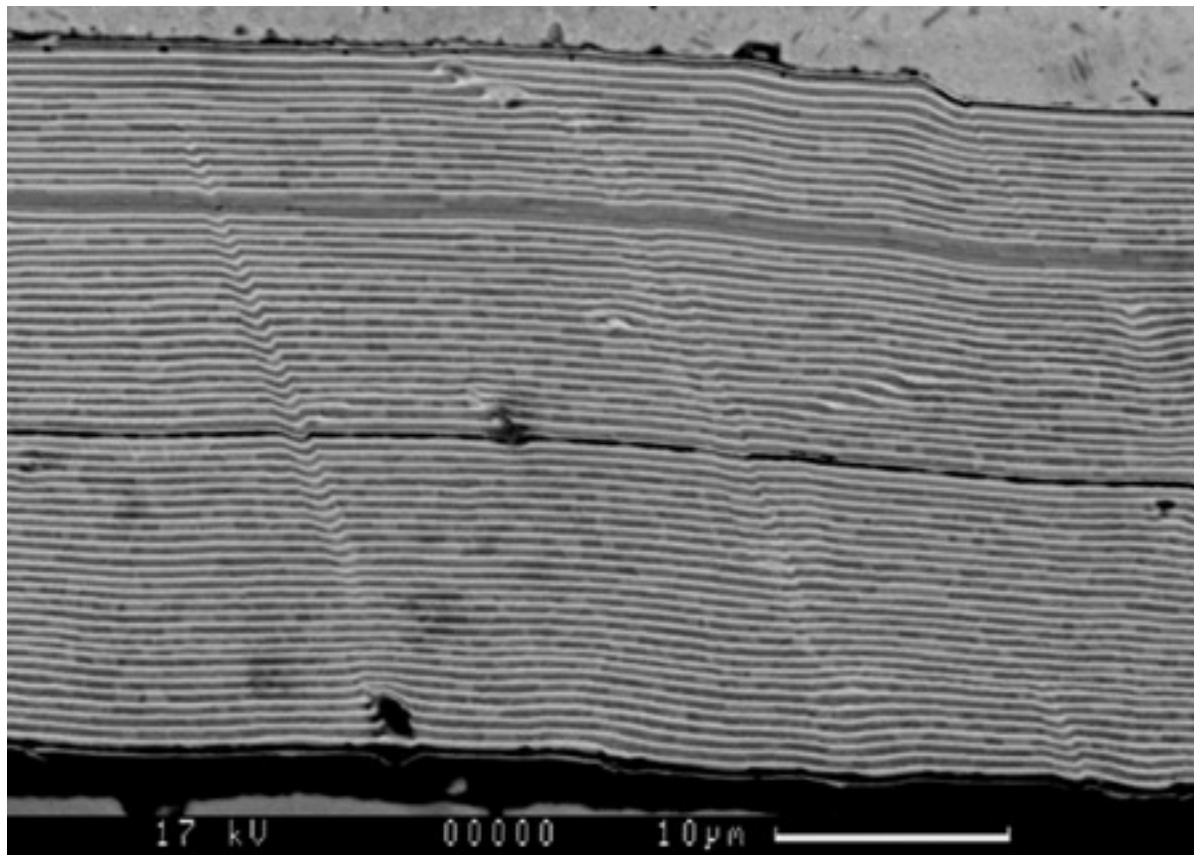


NiTi hexagonal honeycomb  
(5.7% dense, 0.37 g/cc)

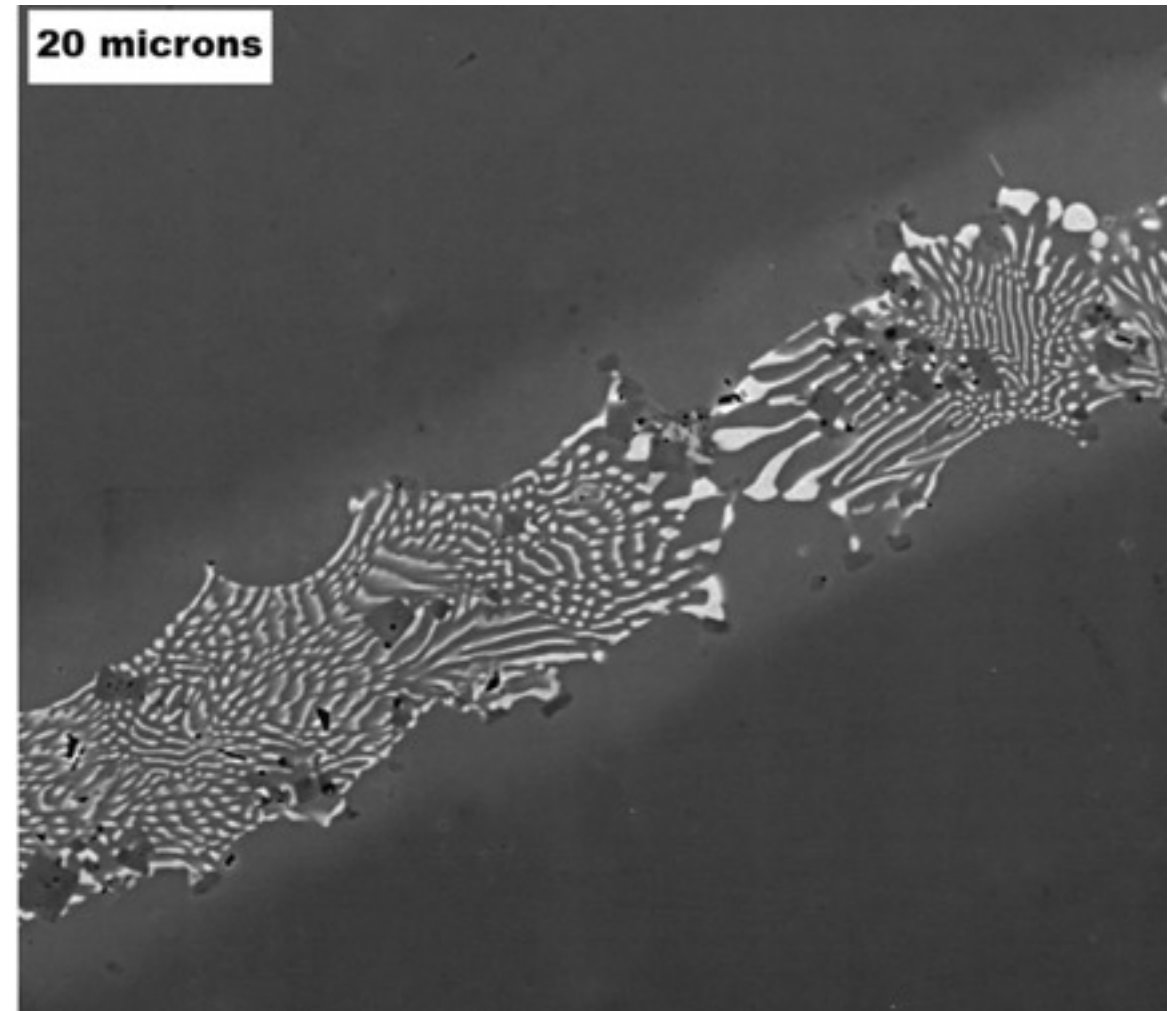


# Aggressive Reaction





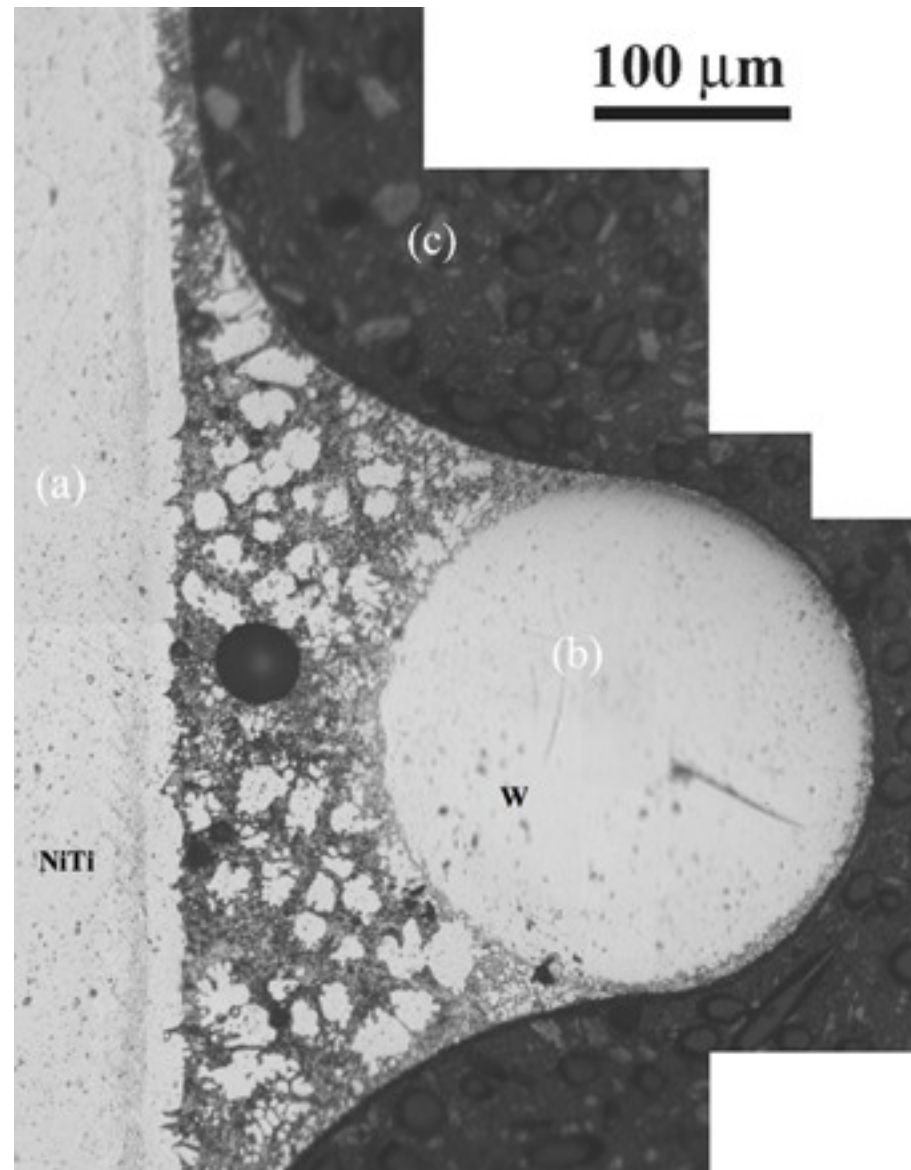
NiTi-Nb multilayer braze foil cross-section  
(127 layers, 34 micron thickness total)



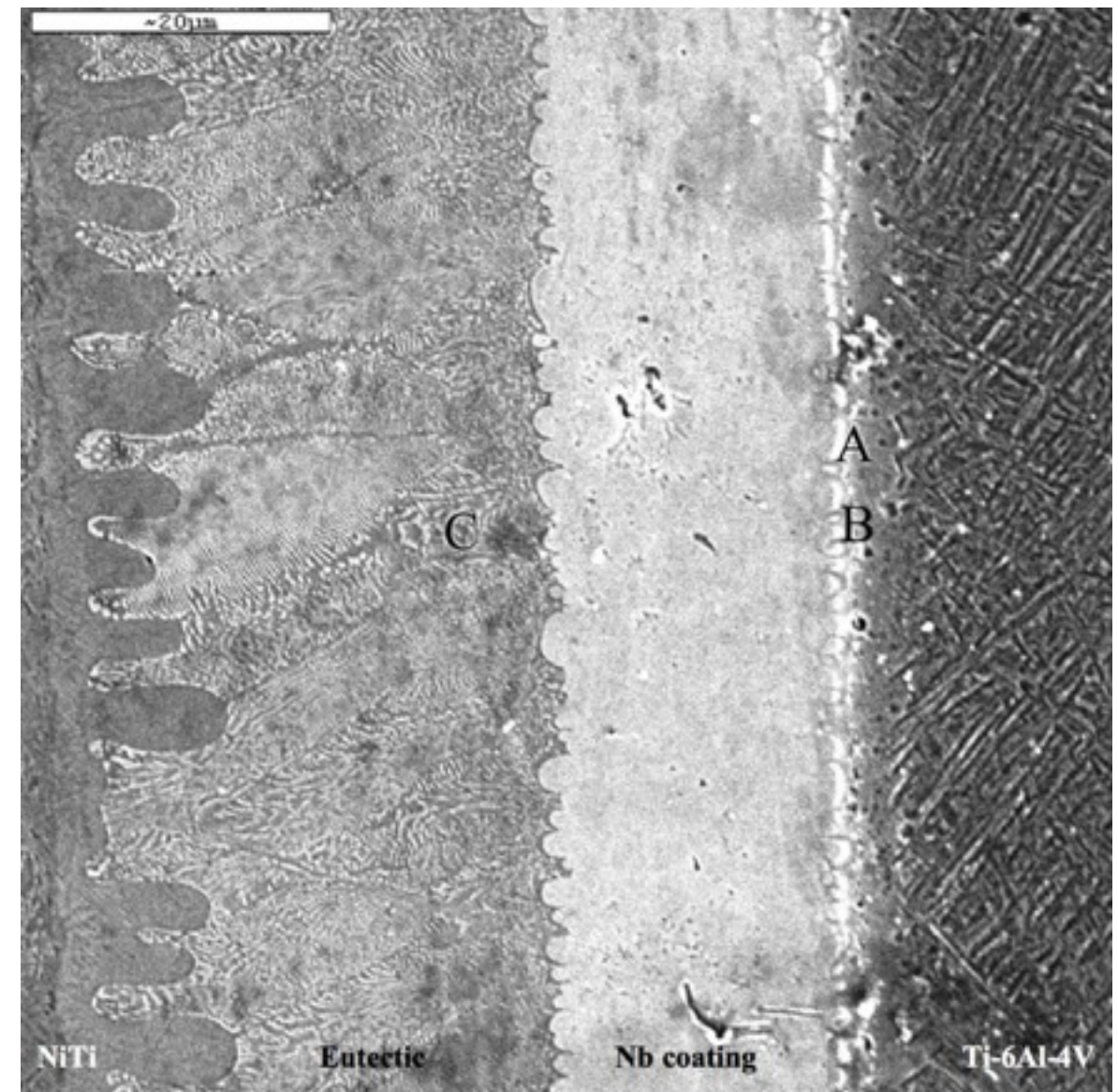
Braze microstructure using  
multilayer foil



## Other Heterobonds with NiTi



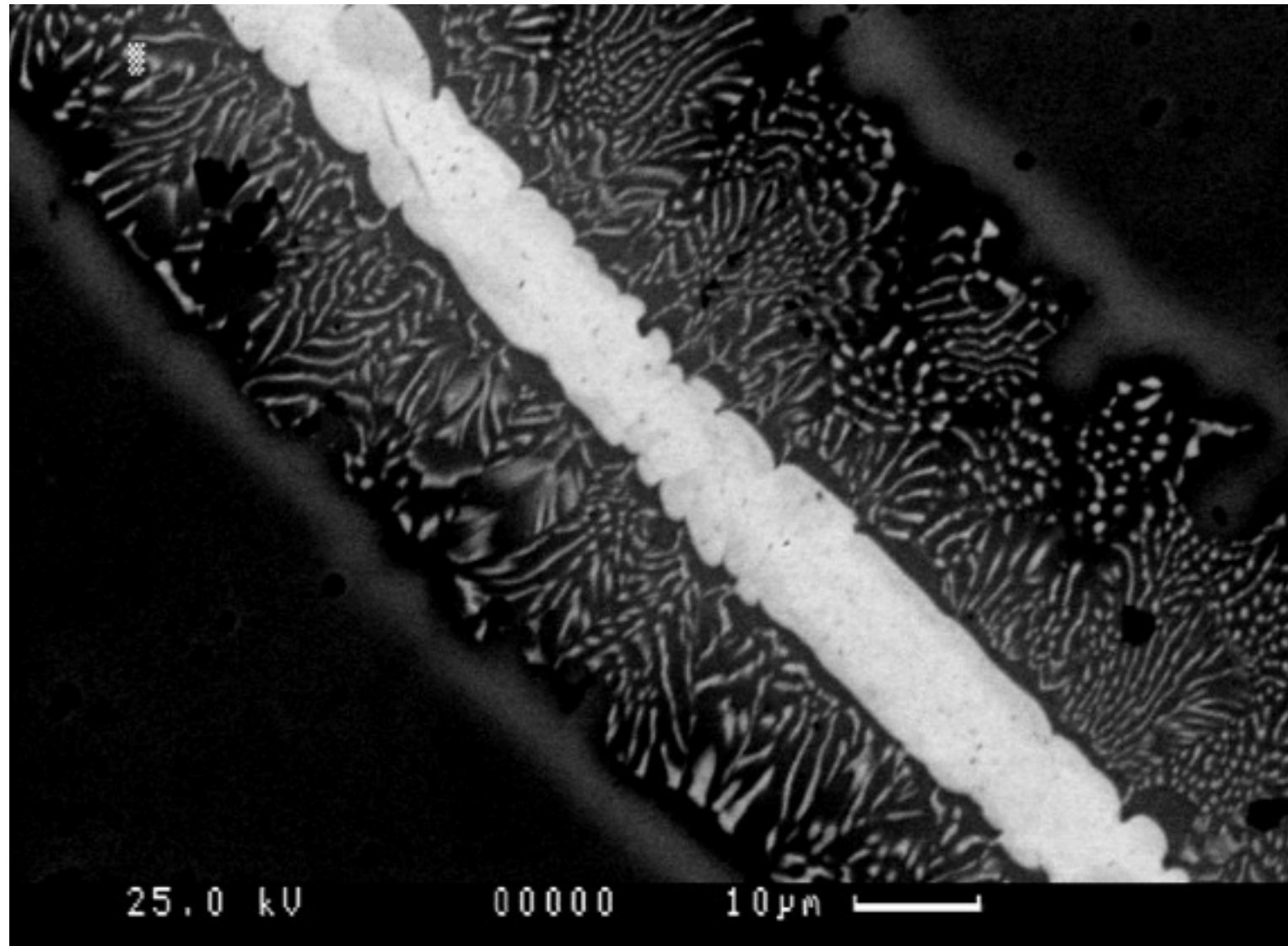
Pure tungsten (W) wire bonded to NiTi alloy



Sputtered Nb layer bonded between NiTi and Ti-6Al-4V



## Possible Braze for High-temperature SMAs



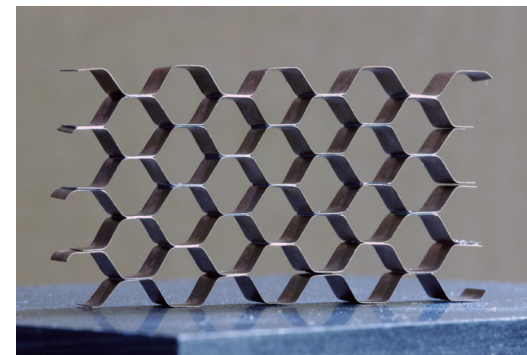
Braze Joint between two wrought pieces of a Ni<sub>24.5</sub>Pd<sub>25</sub>Ti<sub>50.5</sub> HTSMA  
(HTSMA from R. Noebe's group, NASA Glenn Research Center)

## APPROACH:

- Built-up, low density SMA corrugated structures
- Commercially-available wrought NiTi materials
- Nb-based brazing process

## ACCOMPLISHMENTS:

- Fabricated NiTi SMA specimens:
  - hexagonal honeycombs (~ 5% dense)
  - wavy corrugations (~ 5% dense)
  - close-packed tube array (~ 32 % dense)
- Demonstrated robust braze joints:
  - Up to ~800 MPa tensile strength (butt-joints)
- Preserved adaptive properties of NiTi base material
- Improved layup with self-indexing geometry
- Multi-layer foils improve control of braze stoichiometry
- Positive indications that braze process can be used to join other metal alloys and high-temperature SMAs



# Possible topologies & geometries

